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Identifying and Evaluating Recirculation Strategies for Industry in the Nordic Countries

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Abstract: The manufacturing industry in the Nordic countries aims to include closing product and material loops to recover values in their circular economy strategies. Recirculating strategies for products and materials are required for existing products that are part of the stock and are also anticipated to be aligned with products designed for circularity and circular business models in the future. Options to capture value of discarded products are diverse and include reuse, remanufacturing and material recycling. The Circular Economy Integration in the Nordic Industry for enhanced sustainability and competitiveness (CIRCit) project developed a framework to guide decision makers in the industry on how to identify suitable treatments and subsequent use at the end of use or end of life of a product and how to select among different options. Factors considered in the assessment include technical feasibility, necessary efforts, networks of business partners, legal implications and overall sustainability aspects. Our empirical studies show great support for decision-makers in the value recovery of different products with different complexity levels. It is also concluded that the properties of products at their end of use are the main drivers behind selecting a proper recirculation strategy. This study contributes with an empirical evaluation and a consistent terminology framework for recirculation options. The general setup is relevant for the Nordic countries.

Keywords: closing the loop; resource recovery; performance economy; reuse; repair; remanufacturing; refurbishment; repurpose; material recycling; cascading

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1. Introduction

Circular economy (CE) measures are generally proposed to reach sustainability goals and reduce climate impacts while emphasizing the conservation of finite resources, which are circulated in economic loops or substituted by renewable and biobased options where possible [1,2] An identified gap is to explicitly show how different CE concepts are applied in practice in a wider range of companies [1,3]. The CIRCit research project includes several focus areas: one addressing recirculation strategies, which is further elaborated here. Publications that focus on other aspects include circular product design [4], circular business models configuration [5] and digitization aspects [6]. A common systematizing tool (strategies scanner) was developed and previously presented at [7] to map and visualize companies' opportunities in terms of circular strategies. Within the general strategies scanner, strategies to recirculate products and parts and strategies to recirculate materials were addressed as integral parts. These are displayed in context with links to other contributions to CE, such as the product development stage, which considers the utilization of secondary sources.

The subset of recirculation strategies for products and parts is based on using products or parts at the end of a use phase after a possible transformation and treatment process for a similar or different purpose. Strategies for recirculating products and parts include upgrading, repair and maintenance, reuse "as is," refurbishing, remanufacturing, and repurposing. The strategies have in common that the structure of a product or part remains intact (or partially intact), and no fragmentation process is foreseen for existing products before they enter a new use cycle. Processes that allow for the recirculation of products and parts are at times subsumed as value retention processes (VRPs); however, the scope and terminology related to VRPs vary across industry sectors and the literature [8,9]. The European Remanufacturing Network (ERN) uses the term remanufacturing broadly and includes examples of upgrading, reuse, and refurbishing. A common feature of remanufacturing according to the ERN is the high quality of output products exemplified in a market study [10] and a collection of case descriptions ("case tool") available at https://www.remanufacturing.eu/case-study-tool.php (accessed on 11 November 2021). The summarized approach does not provide a consistent framework from which to identify and distinguish between options.

Products or components that have reached a state where they cannot be used anymore, possibly after several use cycles, have reached their end of life and are preferably directed to material recycling and energy recovery. In this case, a fragmentation of the product or part is intended or accepted to generate clean input flows for material processing. In general, material recycling is preferred over energy recovery, which is occasionally called measure of last resort. For specific cases, energy recovery may be preferable, such as when the material contains unwanted substances that are not accepted in products brought on the market under current legislation [11]. Moreover, decisions on energy recovery need to consider a wider set of aspects, such as local constraints, social concerns, political considerations, and economic, environmental, and technological aspects. These criteria often conflict with one another and require an approach that objectively considers different dimensions. Reference [12] address such complexity with a Multiple-Criteria Decision Analysis (MCDA) based tool for better informed decision making, enhanced awareness, and empowered communities. A transition to a circular economy implies that basic parameters are expected to change; the framework thus needs to consider current conditions for products developed largely for a linear economy while also accounting for trends in product development for a circular economy.

In the Nordic countries, the collection of end-of-use consumer goods creates additional logistical challenges stemming from large areas with low population density, and the need to mix road, rail and sea transportation modes adds to the complexity of establishing efficient logistics for recirculation. The challenge is to obtain the right materials in the right volume at the expected cost [13]. For manufacturing industry aiming to increase recirculation activities, a consistent framework and terminology to identify, assess and evaluate opportunities for building end-of-use and end-of-life strategies is lacking. This gap is addressed here by providing a consistent framework to support the identification of a suitable recirculation strategy for a selected product in the market based on five main characteristics at its end-of use or end-of-life stage. The framework is demonstrated through application in five companies.

The proposed framework for recirculation strategies has been developed in several steps within the context of the CIRCit project. The concept for evaluating recirculation strategies has been previously presented in [14]. The framework has been co-created, tested and validated by manufacturing companies throughout the project, leading to a workbook [15]. In this paper, we apply the concept for co-creation and additional validation cases. In the following sections, the research methodology used is presented in Section 2; the theoretical framework adopted is presented in Section 3; the results are presented in Section 4. A discussion and final conclusions are presented in Sections 5 and 6, respectively.

2. Materials and Methods

The research and workflow adopted in this paper follow the design research methodology (DRM) [16]. The DRM was selected to develop a consistent framework to assess recirculation strategies. Design thinking provides a direction for research of a transitioning environment and helps identify important theoretical and practical issues that need to be addressed with limited information in a collaborative effort [17,18]. Table 1 shows the phases and respective activities and outcomes of each phase with several iterative loops between the DRM phases.

Table 1. Research and workflow presented in this paper.

Research Clarification (RC)	
Main activities • Literature overview of the CE with an emphasis on recirculation.	Main outcomes • Overview and understanding of circular strategies. • Development of an initial circular strategy scanner. • Understanding of recirculation strategies as a subset. • Delineating properties of economies in the Nordic countries.
Descriptive Study I (DS I)	
Main activities • Complementary literature overview. • Internal workshop (CIRCit). • Workshop series with companies.	Main outcomes • Distinguishing strategies for the circulation of products and materials—focus group. • Existing frameworks adopted in the literature. • Identifying the four main recirculation aspects. • Initial development of the framework.
Prescriptive Study(PS)	
Main activities • Co-creation case studies: Workshops, visits, interviews and observations Internal workshop and meetings.	Main outcome • Connecting recirculation and other focus areas. • Trying out the initial framework with 3 companies (co-creation). • Identifying information needs in industry for decision support.
Descriptive Study II (DS II)	
Main activities • Webinars. • Internal workshop and meetings. • Investigation of circulation cases. • External validation and tool application.	Main outcomes • Validation of the framework. • Concluding learnings points and improvement potential to the framework. • Finalizing the latest version. • Presenting the framework to several manufacturing companies, researchers and consultancies. • Application of the framework with additional companies beyond those involved in the CIRCit project.

2.1. Research Clarification

The research clarification phase included an initial literature search to identify gaps, build a theoretical framework and identify the research goal. This was carried out as a collaborative task through the project with each focus area adding its perspective. Generally, the literature search involved a keyword search of scientific databases including ScienceDirect for peer reviewed publications, CiteseerX, the Bielefeld Advanced Search Engine (BASE), the Nordic DiVA portal for open access publications, gray literature, and reports. Reports were also retrieved from specific repositories provided by relevant institutions such as the Ellen Macarthur Foundation (EMF), the European Commission's DG Environment, the European Environment Agency (EEA) and the United Nation's International Resource Panel (IRP). Snowballing references was used to identify additional input. The keywords used include circular strategies, and for the case of recirculation, in particular remanufacturing, refurbishing, recycling, upgrade, repair and reuse. This collaborative effort led to the initial circular strategies scanner 4.

Based on the literature search, a high-level approach to identify criteria for strategic decision support was developed that includes technical properties such as feasibility and viability of re-processes and organizational and institutional aspects such as means to collaborate in an industrial symbiosis with a neighboring industry or options for establishing closed-loop supply chains. In addition, regulatory barriers, e.g., for goods transported across borders, were identified as important aspects of the analysis in the descriptive and prescriptive stages, forming the concept used in the focus area recirculation strategies 10.

The research addressed industry in the Nordic countries; therefore, this stage also included a delineation of common characteristics for the included countries and of whether similar characteristics can be found in literature examples covering a different and larger population.

2.2. Descriptive Study I

Descriptive Study I aimed for a deeper understanding and distinguishing of circular strategies. In this phase, closing the loop strategies as a subset were further explored in a complementary literature analysis including literature on "remanufacturing", [19] "disassembly" and "design for recirculation' [20] and recirculation frameworks as proposed by the International Resource Panel [8,9,21]. As an integral part of the strategies scanner, six recirculation strategies for products and parts and three recirculation strategies for materials were distinguished based on their potential contribution to transfer value to subsequent use cycles and life cycles, and on the expected effort to implement them. Published examples from databases and literature were used in this study in workshop discussions held in five Nordic countries with a total of 30 participants mostly from industry functioning as expert focus groups. The quality of the results was strengthened by the interactive research design, where the researchers had an influential role in the continuing initiation, testing and implementation of the strategies with the companies [22].

2.3. Prescriptive Study

This phase involved co-creation research efforts with companies using their own products as case study to further develop and refine the framework and establish a process evaluation map. The co-creation was carried out with three companies and for multiple cases in each company. Each co-creation company was involved in at least two focus areas, including recirculation strategies and circular supply chains. Companies participated with three to seven experts from different functions, including purchasing, sustainability management, waste management, quality management, aftersales, and product design. The meetings were carried out in person and virtually with an exchange of documents occurring in between over a period of six weeks to three months. The data provided by companies for recirculation strategies included bills of materials of existing products and supply chain information, quotations and contacts related to previous recirculation efforts and were complemented with interview and observation data collected during visits on site. Cases were treated separately to include aspects for a wide variety of products. The aim of co-creation was to identify how existing products are currently handled at the end of their service life and which recirculation options are established or are available for similar products.

The analysis of all five aspects to assess recirculation options was performed together with participating companies to evaluate the tools, procedures and guidelines for identifying ways to close product cycles as decision support. The research uses action research to include practitioners and decision-makers in processes of scoping, initial data collection, option selection, evaluation and the further investigation of the most promising alternatives where necessary. Cases A and B illustrate the results of the prescriptive study.

2.4. Descriptive Study II

This phase was used to validate the concept and framework with additional companies that were not involved in the project. Webinars were used to disseminate the results, receive feedback and initiate the further development of the framework in the community. As an additional round of validation extending beyond the CIRCit project, validation cases were investigated together with researchers who were not involved in the initial study via interviews with practitioners. Cases C, D and E illustrate the results of descriptive study part II.

The cases are intended to enhance qualitative understanding of the studied concepts [23] and show why and how strategies can be applied but do not prove the robustness of a certain strategy.

3. Framework and Context

3.1. Conditions in the Nordic Countries as a Starting Point for Establishing Circular Economy

Economies in the Nordic countries can be considered as performance economies, meaning they are well developed, mature and saturated [24]. Households and businesses are equipped with products to an extent that is satisfying basic needs and beyond, and an inventory of goods and infrastructural facilities (summarized as stock) is built up in society. Purchases of new goods are in this case potentially based on fashion or trends, and not necessarily on loss of function for existing goods, thus providing limited options for growth [25].

This also implies that the reasons to replace a good are varying and goods reach the end of a use cycle not necessarily at end of technical function, but also when they are perceived by their owner as no longer suitable, e.g., when the user (owner) demands have changed and the size or other properties are no longer suitable, or when newer versions of a product with additional properties are available. Therefore, a shift to circulation approaches can be particularly beneficial to maximize the utilization of resources.

Geographic preconditions between the Nordic countries vary. As an example, Finland, Norway and Sweden cover large areas and Iceland has a small population and nondomestic markets for goods always require long-distance transport, whereas Denmark shows similarities to continental European countries in terms of population density and distances to trade partners.

Collection systems for several materials are well established in the Nordics, and a positive attitude toward recirculation can be expected. Differences between countries can be used to identify drivers and barriers for strategies; for example, incineration with energy recovery is well established in Finland, Norway, and Sweden with large district heating networks, whereas in Iceland with its high availability of geothermal energy, this path is less developed.

3.2. Recirculation Strategies as a Means to Achieve Resource Efficiency for Existing Products

Recirculation strategies adopted in the Nordic countries need to consider the value in stock as an opportunity to increase resource efficiency through using existing recirculated products and materials as well as cutting-edge production technology to contribute to sustainable development via recirculation [26,27].

A general expectation is that future products that are designed for circular economy will consider requirements that allow for recovery of values from entire products, components, and materials through reuse and reprocessing [28,29]. Other contributions to conserving values that are expected with circular economy are emphasized frequently, such as application of novel business models built on service and functions or shared use instead of ownership of a physical product [30]. Analyzing the recirculation of existing products can serve as an input to further develop design and business strategies.

One example is the analysis of design choices regarding assembly and joining that were adopted in the past and may now prevent the retention and recovery of value. Where materials and components were permanently joined (for example, via welding or gluing), it can be difficult to separate them in a manner that allows for the recovery of all components in a clean state necessary for high-quality secondary resource use. In this case, separation processes that favor one material and sacrifice another can still be an option.

Existing products can contain higher concentrations of substances not identified as hazardous at the time of production, but for which subsequent requirements for restriction or authorization have been introduced, such as heavy metals and persistent organic chemicals used in electronic goods. Conversely, existing products might also contain higher concentrations of valuable materials and are a rich source for resources that are becoming increasingly scarce.

Many recirculation approaches have been developed and refined in the last decade. Therefore, an analysis of existing techniques focused on purpose (P), requirements (R), application areas (A) and general aspects (G) is used as a starting point and combined with their potential to transfer value to a subsequent use cycle.

3.3. Categorizing Recirculation Strategies

Recirculation processes for products and parts are distinguished from recirculation processes for material due to their potential to reclaim value from both materials, and manufacturing processes contribute to the value of a product [31]. Material recycling aims to retain material value [32], processing efforts that contribute to the value of a component are lost when products and components are fragmented, and materials are separated.

The initial use of a product might, however, be no longer needed due to technological development, and recirculation is therefore not an option for all products.

Recirculation strategies for products and materials were included in the strategy scanner as an integral component. To address opportunities for implementation, their specific contributions to resource conservation, requirements and application areas were further specified. The subset of recirculation strategies is summarized in the following Table 2.

Table 2. Recirculation strategies of the circular strategies scanner developed and used in the CIRCit project [7].

Recirculate products and parts	Upgrade Repair and maintenance	Extend to existing use-cycles	Order of preference ↓
	Reuse Refurbish Remanufacture Repurpose	Extend to new use cycles	
Recirculate materials	Recycle Cascade Recover	Effective application at end of life	Order of preference ↓

The order of preference is based on a qualitative delineation of several characteristics.

Potential value transfer to a subsequent use cycle based on material input for the initial use cycle—high is preferred over low.

(a) Potential value transfer to a subsequent use cycle based on initial manufacturing or processing effort for the initial use cycle—high is preferred over low; updated products with high perceived value are preferred over reuse.
(b) Level of intervention (energy and processing effort) for actual recirculation processes; low is preferred over high; both refurbishing and remanufacturing require more effort to facilitate a new use cycle.
(c) Material loss from the product enables recirculation—low is preferred over high.
(d) The addition of value during the recirculation process—high is preferred over low.

The following sections describe recirculation strategies along with their purposes, requirements, potential applications and general characteristics as used in the project. According to the common framework logic, the nine strategies are characterized based on their contributions to value transfer, required intervention and the performance of subsequent use cycles.

3.4. Recirculation Strategies for Products and Parts

Note: the analysis of possible strategies focuses on the purpose (P), requirements (R), application areas (A) and general aspects (G) of each viable recirculation option, see Tables 3–8.

Table 3. Analysis of the recirculation strategy: upgrading.

P	Purpose: To extend an existing use-cycle by adding value or expanding functions relative to previous versions.
R	Requirements: Requires intervention but also allows value addition and is therefore considered the most preferred.
A	Applications: Required for products that are in full working order or generally in working order, typically when a new generation of similar products is available and older products are perceived to be outdated.
G	General aspects: Suitable for products that are essentially functional but do not meet evolving quality and performance requirements customary in the market. The upgrade strategy extends product value by enhancing the function of an existing product to even beyond its original design condition and reducing value loss by enabling a continued use of parts and products. Electronic devices can also be upgraded based on new software versions.

Table 4. Analysis of the recirculation strategy: Repair and maintenance.

P	Purpose: To extend an existing use cycle when failures occur by countering wear and tear and correcting faulty parts of a defective product to return it to its original functionality.
R	Requirements: This strategy includes corrective, condition based, predictive and prescriptive maintenance. Repair as a specific form of maintenance may involve the restoration or replacement of faulty parts.
A	Applications: For products that are generally in working order but have developed flaws and/or occasional failures.
G	Must be performed when a product or part is not functioning or not functioning reliably, resulting in the need to replace or fix parts. Repair can also be performed by the product owner and can in this case be supported by providing repair kits with spare parts and tools.

Table 5. Analysis of the recirculation: Reuse.

P	Purpose: Extend to new use cycles by reusing a part or product that has been discarded or is not in use but still in good condition and can fulfil its original function in a different use context (new customer/user).
R	Requirements: Foresees a second or subsequent use of the same product after reaching an end of use without significant repair or other intervention.
A	Applications: For products in full working order but for which the previous user's needs have changed and adaption to another application context is not possible. The first use cycle is not extended, and no additional warranty claims are provided.
G	General aspects: Reuse requires less intervention than upgrading or repair but also cannot provide a similar level of value transfer.

Table 6. Analysis of the recirculation: Refurbish.

P	Purpose: Extend to new use cycles by returning a (faulty) part or product that has been discarded or is not in use by the current owner in satisfactory working condition. The working condition may be inferior to the original specification.
R	Requirements: This strategy foresees a second or subsequent use of the same product after reaching an end of use with repair or another intervention.
A	Applications: Products that are generally in working order but have developed flaws and/or permanent failures, including products that have been accidentally damaged. The first use cycle is not extended, and limited warranty claims are provided.
G	General aspects: This strategy is used in different industry sectors and also termed reconditioning, retrofitting, refreshing, and remodeling. Refurbishment does not involve bringing products to as-new condition and the actual condition is often less clearly specified relative to which is achieved through remanufacturing. However, the term "comprehensive refurbishing" is also used and indicates higher effort but also higher value transfer to the subsequent use cycle.

Table 7. Analysis of the recirculation: Remanufacturing.

P	Purpose: Extend to new use cycles by returning a product that has been discarded or is not in use to at least OEM performance specifications and quality.
R	Requirements: To rebuild and restore to as new or higher performance based on cores, parts and products that show significant wear and damage and need substantial intervention. Remanufacturing generally occurs in industrial settings.
A	Applications: For products that are in limited working order and have developed serious flaws and/or permanent failures; products have been damaged during an accident.
G	General aspects: For traditional product sales, a warranty that is at least equal to that of a newly manufactured equivalent may be issued when a remanufactured product is sold. Remanufacturing requires more effort than refurbishing. An industrial setting either at the original manufacturer or a specialist collaborator is implied.

Table 8. Analysis of the recirculation: Repurpose.

P	Purpose: Extending to new use cycles by finding different functional uses.
R	Requirements: This strategy aims to find alternate uses for products at their end of use.
A	Applications: For products in limited working order with serious flaws and/or permanent failures and for those that are outdated but have a structure/shell that is still usable. It is also applicable if the initial use of a product is no longer in demand and for limited application contexts.
G	General aspects: Repurposing generally implies that a limited set of the initial product or part properties is used in a further use cycle. This could include the shell of the product, specific parts, and aesthetic features related to the design where applicable.

3.5. Recirculation Strategies for Material

When the structure of a product is no longer suitable or safe for further use, the recirculation of products and parts is not considered an option. Value transfer to further use cycles is possible using fragmentation and using materials as input for processing, often together with virgin raw materials. Processes potentially used in this case include disassembling, fragmentation, separation and sorting. Material reclaiming strategies include recycling, cascading, and recovering, see Tables 9–11.

Table 9. Analysis of the recirculation: Recycling.

P	Purpose: Extend the lifespan of materials by processing products to obtain input materials of the same or comparable quality for a wide variety of new applications.
R	Requirements: Reprocessing materials to recover some of their properties, often for a similar product.
A	Applications: For products in severely limited working order, that have developed serious flaws and/or permanent failures, that are outdated, with components that cannot be economically reclaimed; and that are perceived to be of low value despite including potentially valuable material constituents. Generally, the strategy also applies for single use products.
G	General aspects: Due to fragmentation and processing, recycling can to a limited extent also be used to refine raw materials and remove unwanted constituents. Established recycling processes do not necessarily use this option and are rather designed to accept large quantities of inputs and the quality of the output is not in all cases considered as valuable as materials from virgin sources.

Table 10. Analysis of the recirculation: Cascading.

P	Purpose: Extend the lifespan of products by processing them to obtain input materials for a wide variety of new applications; declining quality of properties is accepted.
R	Requirements: Reprocessing products to recover materials, often for a different product.
A	Applications: This strategy is applicable for products in severely limited working order, that have developed serious flaws and/or permanent failures, that are outdated, that have components that cannot be economically reclaimed, and that are perceived to be low value. Generally, the strategy also applies for single use products.
G	General aspects: Cascading implies that a subsequent use significantly transforms the chemical or physical nature of the material and often involves a deterioration of material utilization and quality, such as when materials cannot be used on the exterior of products anymore but in nonvisible applications or as counterweights or ballasts. Cascading can be a suitable means to produce very robust and long-living goods. While further processing is not an option, utilization is as high as possible due to a long use phase.

Table 11. Analysis of the recirculation: Recovering.

P	Purpose: Achieving energy or nutrient recovery from the product or part when all other options fail.
R	Requirements: Limited processing of products before the recovery process where the posttreatment of unrecovered/rejected fractions is required.
A	Applications: Different types of products, such as products or components that are consumables and used to capacity; products that are too complex for disassembly and that do not contain ingredients that are specifically valuable or hazardous.
G	General aspects: Recovering aims to utilize a limited set of properties of the discarded product or part, such as calorific value or nutrients and fertilizers; more sophisticated processes are under development to utilize biobased resources for nonfood application and prevent competition with use as food, characterized as "bioeconomy 2.0" or second-generation biomass use.

3.6. Assessing Recirculation Strategies

Companies that have identified one or more recirculation strategies as suitable need to understand the potential to implement them in practice.

The analysis is designed to consider: (1) the technical feasibility of recirculation processes, (2) necessary efforts for establishing feasible processes, (3) potential market partners, (4) legal implications for producers, and (5) overall sustainability aspects. All five aspects must be approved for the implementation of a circular strategy and are described further in the following sections.

Based on the classification of recirculation strategies, the assessment procedure from a manufacturer's perspective includes several steps.

For the recirculation of products, the reason to retire or discard a product from a customer's perspective also determines the state of a product and whether it can be reused, upgraded or repaired or needs more intervention. For the recirculation of products and parts, technical feasibility requires that the condition of a product can be assessed for safe application in an additional use cycle according to industrial standards. If there are reservations due to a lack of testing methods or reduced functionality, the product can be used to a certain but more limited extent. Examples include reuse as-is without warranty or refurbishment to working condition with limited warranty.

When principal strategies are identified, manufacturers need further information to identify whether a technical process for recirculation is already established and whether solutions available at the laboratory and pilot scales can be upscaled to the extent needed.

Processes that are technically feasible need to be further investigated in terms of means to implement them in a viable manner. Where the effort required for implementation is high, this can also imply that environmental sustainability cannot be achieved. Feasibility and viability are evaluated together to understand if a product, part or material is in principle suitable for recirculation and if such recirculation has the potential to contribute positively from a sustainability perspective.

Where recirculation processes are not implemented for a specific manufacturer, necessary networks and organizations to facilitate new collaborations may need to be established. Advantages of networks include larger flows of products and parts or materials to be processed, complementary demands in industrial symbiosis and complementary competencies. The need to establish a specific network for a particular recirculation strategy can be evaluated by mapping competencies and expected volumes available in-house and considering whether they are sufficient in scope, competency, technology and capacity to execute an independent recirculation strategy.

Among the barriers to recirculation strategies that are acknowledged by manufacturers are legal requirements and requirements defined by customers regarding compliance with standards and warranty claims. While this layer can prevent an implementation of recirculation at a given time, it can also be a temporary barrier.

Sustainability aspects of recirculation need to be considered across all layers and are connected to properties of the recirculation output and whether there is a demand to use it; processes that are technically feasible but not clearly viable also bear a risk of being unsustainable. The evaluation of areas related to technical aspects can be used to determine whether planned recirculation has the potential to reduce resource demand, which is a prerequisite for environmental sustainability.

Recirculation is intended as a measure to reduce demand for virgin raw materials, which has a direct relation to energy usage and emissions from mining and processing. Thus, the potential to contribute to environmental sustainability is expected.

4. Empirical Results

4.1. Results of Focus Group—Descriptive Study I

A series of workshops was held in five Nordic countries to introduce the framework and focus area to industry partners and raise interest for the following phases. The categorization of recirculation strategies was introduced based on case examples from the literature and databases. Based on feedback from the participating industry, a cursory evaluation of legal aspects of recirculation strategies was incorporated as a mandatory element to address concerns regarding responsibility for recirculated products and the shipping of end-of-use products across national borders. Aspects that need to be considered for the evaluation of recirculation strategies were identified as the feasibility and viability of recirculation processes as core requirements, and organizational questions regarding collaboration, networks and legal requirements were included as framing conditions.

4.2. Results of the Detailed Cases—Prescriptive Study

Cases were included in the series as co-creation (A and B) and validation cases (C, D and E). Cases A and B involved both descriptive and prescriptive study (see Sections 2.3 and 2.4), while additional validation (see Section 2.4) was performed with researchers not involved in co-creation to validate the applicability of the framework (cases C, D and E). The validation cases involved SMEs selected with a range of product life lengths from short (e.g., packaging) to long product lives (e.g., houses), thus ensuring that the framework's applicability to a variety of products and materials.

Case A: Carbon fiber cuttings from medical equipment (orthopedic products) tailored for individual customers. Currently sent to landfill.	
Feasibility of recirculation:	Feasibility product recirculation—none, tailormade products in a sector with high legislative quality demands. Includes the recirculation of parts. Feasibility of processed material recirculation: identified, advanced composite to composite recirculation is offered by two specialists, one in Great Britain and one in Germany. Both prefer a closed loop, as the demand for recycled carbon fiber material on the market is currently low. Not an option for the original application; needs to include an acceptor in a network. Feasibility of cascading: identified, carbon source required by metal processing industry in the vicinity; cannot be met by locally sourced biomass.
Viability:	Limited viability of material recirculation due to transport effort from northern Scandinavia to processing location and further to a dedicated acceptor. Cascading as a viable recirculation option with short transport distances replaces other carbon sources that require transport.
Organization and networks:	Organizational effort for material recycling is expected to be high; potential acceptors in the automotive industry need large volumes that cannot be met. Organizational effort for cascading is expected to be moderate; the acceptor is available to investigate parameters.
Legal:	Legal state of material recycling needs further evaluation for companies from Iceland/Norway to investigate transport across EU borders. Legal state of cascading shows no legal barriers.
Sustainability aspects:	The case of provided processed carbon fiber material for secondary materials could contribute to resource efficiency, as the carbonization stage can be avoided in a secondary life cycle. Long transport distances and related emissions must be balanced with potential benefits. In the case of cascading, only carbon and energy content is used in a subsequent application. Due to avoided transport for alternative material, this option could contribute to sustainable development.
Conclusion: the information search and evaluation provide insights into the limitations of advanced material processing. Cascading utilizing a limited set of properties in a regional context can be implemented. Revisiting the case where a dedicated acceptor or increased market demand can be observed is recommended. LCA studies for similar products with contributions of raw material and processing to environmental impacts were seen as helpful.	

Case B: Office furniture/interior module: Office booths with soundproofing and ventilation are produced in a Nordic country and shipped to customers in Nordic countries and worldwide. The products are large and heavy with double glazed windows and wood contributing most to their weight. Connections to plug-in electronic devices and interior furniture are built in. The high value products are provided to upmarket customers. Due to the novelty of the module, none of the products show high levels of wear or require intervention.	
Feasibility of recirculation of products:	Upgrade and repair: Options to upgrade and repair (electronic equipment and furniture) provided via aftersales services and distributing networks possibly also using a kit and service are provided and can be expanded. Note: interior covering is partially glued on and is destroyed or damaged during disassembly. Reuse to second-hand markets is not actively supported but can be a means to reach broader market segments. Refurbishment on site/at client provides opportunities, as does remanufacturing at the original manufacturer's location. Repurposing is similarly an option for the future.
Feasibility of recirculation of materials:	Damaged parts such as glass panels or worn furniture are suitable as input flows of established and emerging material recycling processes both for recycling and cascading at the customer's location. Examples include laminated safety glass to be treated together with windshields (recovery of cullets and polymer layers), electronic equipment, and furniture. Customer information for such aspects has been added to manuals and will be expanded based on increased knowledge. Energy recovery for materials with sufficient calorific value (wood and polymer-based interior material).
Viability:	Upgrading, repair and refurbishment: offering repair kits to be used at the customer's location provides business opportunities with limited effort and can be extended to refurbishment with larger interventions. Reuse: Used products are occasionally offered via websites by owners; official marketing of used products "as is" is not used. Transport and interventions might become necessary if sales are organized through the manufacturer. Remanufacturing: Transport to the manufacturing site requires the disassembly and long-distance transport of heavy products; this strategy therefore needs to be evaluated on a case-by-case basis. Recycling and cascading: this is possible in many locations, and it is necessary to explore legislation and implemented facilities at the user's location. Recovery: For energy recovery, a partial disassembly and removal of metal parts, electronics and glass is required.
Organization and networks:	Using dedicated sellers or dealerships in different countries is established and options to include further recirculation practices need to be explored. In particular, local infrastructure for recirculation must be checked for different locations.
Legal:	Legal and warranty constraints are not seen as prohibitive. The buyer's location is relevant.
Sustainability aspects:	With the exception of remanufacturing or other recirculation strategies that require transport back to the original manufacturing site in Scandinavia from customers among others in California, South Asia or South Africa, strategies to expand the use of the product are expected to make a positive contribution to sustainability.
Conclusion: The information search and evaluation provided insights; recommendations for customers were drafted to incorporate examples and enable suitable treatment at the buyer's location. Advanced material recycling methods for damaged parts are now recommended. Due to the weight and size of the product, a return to the factory was identified as less preferred. No end-of-use products are currently available.	

Case C: Industrial packaging validation case: protective PE foam transport packaging is designed for reuse between the supplier and OEM; the packaging supplier offers a take-back option for the closed-loop material recycling of damaged packaging (clean and monofraction).	
Feasibility of product recirculation:	Upgrading is not seen as an option. Repair and maintenance: repair is feasible at the packaging supplier. Reuse: feasible and the intended product use; number of use cycles is not known by the packing producer and is determined by the users (part supplier and OEM in a closed loop). Refurbishment: feasible at the packaging supplier. Remanufacturing: due to the relatively simple structure of the product, this is not a relevant option. Repurpose: Tailored packaging is adjusted for the protection of parts; the strategy is feasible after fragmentation to foam chips as filling material for insulation and similar purposes.
Feasibility of material recirculation:	Recycling: Feasible for clean monomaterials; other polymers and contamination with oils reduce the quality of the recycled product and the protective function thus cannot be guaranteed. Cascading: Feasible for contaminated/mixed foam fractions. Recovery: energy recovery for heavily contaminated fractions.
Viability:	Reuse: option to reduce the amount of single-use packaging for the OEM; requires separate collection system and avoiding contact with lubricants, oils and other contaminants. Separate flow required and effort for logistics. Repair/Refurbishing: Needs further investigation; currently no damaged packaging is sent back; requires sorting and adjusted treatment. Contamination has to be avoided for material recycling. Repurposing: potentially viable if transport distance to processing is short; competes with mass product. Material recycling: viable if closed loop between packaging supplier and OEM/parts supplier can be established. Transport effort and distance need to be evaluated to compare closed loop recycling with open loop cascading and energy recovery. Cascading and recovery: can usually be provided locally; loss of the unique protective function of the original product; requires a constant input of new transport packaging into the system.
Organization and network:	For the recirculation of products and material recycling: closed loop interaction between packaging supplier, OEM and part supplier is necessary to understand requirements for the use and treatment of the products. This is already initiated and can be intensified.
Legal implications:	No legal barriers were found for the recirculation of products, the OEM selects standard packaging, the suppliers use it and the OEM collects and sorts it after use through reuse and recycling.
Sustainability aspects:	PE foam is produced using methane gas and PE and by removing methane gas. The reuse of products where possible decreases the need to produce new packaging and therefore has a higher potential to improve product sustainability than material recycling. The material recycling of clean and separately collected damaged packages after several use cycles can be used as a complementary means. Cascading can also use discarded products to produce other PE plastics or mixed plastics products when the effort for separate collection is seen as too high. In this case, new tailored foam packaging has to be produced consistently.
Conclusion: This product serves as an example of combined reuse and material recycling, which is intended by design. To further improve design, more information on wear and failure causes is relevant and can be provided through an analysis of used containers returned to the producer. From a methodological viewpoint, the case was used to validate the evaluation tool and was seen as a helpful means to investigate recirculation strategies.	

Case D: Modular house parts validation case. Prefabricated house kits intended for short-term use (with disassembly and reassembly at another location) or long-term/permanent use depending on user requirements. Suitable for temporary demand (plots with temporary permission, temporary demand for preschools and more). The modules are use recycled material as input and considering reuse, repair, and repurpose possibilities for design [33]. The structure can be disassembled for the exchange of single modules or for dismounting, moving and reassembling the whole building. The standardized temporary module building is meant to be an economically feasible product provided to the community. The modularity provides a means to update and repair modules.	
Feasibility of product recirculation:	Upgrade: Especially for permanent housing, the modules can be combined to provide more than one level and customized to user demands. Adding balconies and patios is included among these options. In this case, reuse may be hindered. Repair and maintenance: damaged modules or sections can be replaced if damage includes a hole or crack. For the interior, repair and maintenance are also possible as in regular houses. Reuse: The modules are designed for use in temporary (or permanent) buildings, and reuse to second-hand markets is actively supported. Each module is designed to enable disassembly. Refurbish: similar to repair, refurbishment at the housing site is possible. Remanufacturing: The housing modules can be disassembled completely, transported to the producer and reassembled in a factory setting. Damaged modules and sections can be replaced to provide a remanufactured house the original lifespan. Repurposing: residential buildings can be used as preschools, as offices or for other commercial and public uses; usage for storage (sheds and garages) is also an option. Smaller sections can be used as furniture or interior design where applicable.
Feasibility of material recirculation:	Recycling is an option for material from modules and parts (doors/windows and interior equipment), including parts removed during repair; the separate collection of structural modules and parts such as windows, doors and other components. Boards are joined by screws to enable several use cycles and material recycling is an option at end of life. Similar processes apply for cascading (boards for filling materials) and recovery (for modules of sufficient calorific value).
Viability:	Can be achieved for all recirculation options; material recirculation is only recommended at the end of life. For product and part recirculation, logistics for the original factory or assembly points have to be evaluated. The value transferred from the initial use cycle is decreasing, and more value transfer is the preferred option. Business models for recirculation are not established as the products are still new on the market.
Organization and networks:	Production involves the local community and specifically involves a workforce with low skills and experiencing long-term unemployment. The use of tools and equipment must be handled safely without long-term training. The same public partners that help recruit workforces for production are also seen as partners for establishing repair networks. This social innovation aspect is seen as an important contribution to social sustainability.
Legal:	The business model includes end-users in production, which means that liabilities are covered by the owner of the building as for any building.
Sustainability:	The prefab houses are built from nonfossil material to increase environmental sustainability. Modules are partly made from recycled material. No toxic materials were identified. Temporary housing and dwellings can be used where permits or demands are temporary, and a permanent structure that has to be taken down after a relatively short use phase requires more effort. Social sustainability is considered by hiring a workforce with no access to the regular labor market, reactivating it. Many recirculation strategies are possible and should be evaluated further on a case-by-case basis to balance logistics efforts against resource reduction.
Conclusion: The recirculation strategies framework was used to distinguish between and evaluate different options. Currently, most products do not require intervention, and planning for recirculation can build on these insights. Compared to the established ecodesign strategy wheel, recirculation scanning requires more background research, and using databases to extract indicators is not uncommon.	

Case E: Industrial textile process spill. Cuttings are used from a textile process where textiles for curtains and awnings are coated, printed and cut. The spill material includes rejected material with minor quality issues and edges. Currently, the material creates a costly waste for combustion. Alternatives were analyzed for the reuse of fabric or for the recycling of yarn or fiber.	
Feasibility of product/part recirculation:	Upgrading, repair, reuse, refurbishment and remanufacturing are not seen as feasible options. Repurposing is possible in some cases in smaller amounts involving social projects and possibly where an acceptor for smaller parts is available.
Feasibility of material recirculation:	Recycling: the fabric can be shredded and spun into lower grade thread with up to 50% recycled fiber. Feasible for clean monomaterials; not feasible for mixed textile fractions. Recovery: energy recovery for heavily contaminated fractions.
Viability:	Repurposing may be viable if customers who need smaller pieces of a variety of colors and materials can be found. To be investigated for the most common materials. Even giving away the fabric is viable due to high treatment costs. Material recycling: this option requires market analysis effort before a sufficient volume of customer demand can be achieved, through this may be possible within the existing value chain network. For recycling, the fabric also needs to be sorted by quality.
Organization and network:	For the recirculation of products and material recycling, the purchasing company and sales organization need to align with production and manage byflows of product.
Legal implications:	Some copyright implications of the recirculation of some fabrics were found and must be addressed first. Registered designs are not owned by the supplier, and fabrics with patterns cannot be recirculated unless the brand is in agreement.
Sustainability aspects:	The textiles are mainly from fossil-originating fiber and any recycling or repurposing of the fabric will improve the climate impact of the main product.
Conclusion: This product serves as a good example of a difficult but still possible combined case of reuse and material recycling. The first option is of course to reduce quality spill. Contracts regarding copyright may need to be rewritten such that cuts may be reused. To recycle properly, new systematic ways to sort and store the rejected fabric are needed.	

5. Discussion

For industry in Nordic countries, recirculation options for existing products provide opportunities to increase resource efficiency and growth in a mature performance economy. Knowledge and unbiased documentation on recirculation processes are emerging, and opportunities have to be evaluated on a case-by-case basis. The approach presented here is based on generic descriptions to identify and evaluate options for recirculation and support industry partners in systematically collecting and evaluating sufficient information. Workshops held in the co-creation stage with contributors from different functions established recirculation as a cross-disciplinary task. Companies gained competence in identifying and evaluating opportunities and in information searching. Validation with partners not involved in the co-creation of the framework confirmed usability. Interactions occurring during workshops with participants from industry confirm that a lack of systematic and consistent terminology and descriptions is seen as a barrier to identifying and exploring the potential of recirculation strategies. Company representatives also commented that they did not see themselves as experts in the treatment of used products and saw this as a task for specialists, including waste management companies. Legal restrictions related to product properties and warranties and the transport of used and potentially damaged products were also mentioned as reasons to not explore opportunities. In summary, a lack of transparent and trusted information about the area and potential risks, including reputational risks, were identified as barriers.

The complexity of the cases varied; while for case A, a recirculation of products was ruled out for the time being and the analysis focused on which recirculation of materials provides benefits, cases B and D provided opportunities for both the recirculation of products and materials. Both setups are treatable with the framework. For case E, a recirculation of product rests is highlighted and is presented as a potential way forward to overcome barriers.

A concept for the empirical assessment of the effects of recirculation systems needs to include the potential to contribute to overarching sustainability goals. It is necessary to identify benefits and drawbacks of the system and their relations to core product properties and peripheral activities. Existing indicators considered and tested are based on material intensity (MI), energy intensity (cumulative energy demand (CED)), and climate impacts [34,35]. No LCA studies were performed through the CIRCit project, but studies from comparable applications could be used in several cases to support assumptions regarding possible contributions. A repository of reviewed case studies for recirculation strategies is not currently available.

In addition to contributing to the focus area, other focus areas of CE and CIRCit can benefit from the presented results and vice versa. As an example, design for disassembly facilitates recirculation strategies for future products and components. Disassembly time and separation effect can be optimized by using suitable joining techniques [36]. Experiences from the recirculation of existing products can be used to confirm and expand design guidelines for both product design and production process design [33].

The consistent terminology with six recirculation strategies for products/parts and three recirculation strategies for materials allows users to distinguish between different options and evaluate the benefits of repurposing over material recycling, for example. Many case descriptions published earlier will, however, not follow the terminology presented here but will conflate different circles. Compared to established approaches such as the eco-strategy wheel, the concept presented here requires more familiarization and learning effort.

The framework was developed for developed and mature performance economies; where basic parameters such as availability of resources are different, drivers and barriers for recirculation might equally differ from what is found in the Nordic region and applicability has to be tested.

6. Conclusions

For products and organizations to realize the full potential of value recovery, strategies for managing and treating existing products need to be developed in parallel with the design of novel products and services. It can be challenging to introduce the recycling of new components and materials to an existing system [37,38] and to recycle low volumes of old products in a new recycling system. To identify a suitable way of treating products not designed for circulation and that have reached their end of use, several parameters need to be analyzed. To identify a suitable strategy, a life cycle thinking approach that allocates environmental impacts based on quality criteria is considered relevant [39–41].

The systematic analysis based on feasibility proved beneficial. The participation of different functions in addition to environmental and sustainability experts was regarded as a positive means to identify opportunities and highlight existing initiatives. Explicitly addressing aspects in a systematic approach supports structured deliberation processes and reveals available data and data gaps. Cases of varying complexity can be addressed, making the framework useful for simple and complex products and for production rests.

Properties of products at their end of use are main drivers behind selecting a recirculation strategy as well as perceptions of value and knowledge, whether this is based on material inputs, processing values or both.

The results are consolidated based on other focus areas in the CIRCIT project such as product development [4], business model configuration [5], and information technology. The latter is of importance since trends of information and communications technology (ICT) improvement have been proven to be fruitful for adopting the "socially oriented" middle pathway approach for increased synergy, interaction and leverage on the collaborative power within waste management (local) networks [42]. Moreover, considering many criteria as foreseen in the framework requires populating categories with quantitative and semi-quantitative data in the future, for which digitization is expected to be an important contribution. When data are available, tools such as a full or quantitative MCDA provide a relevant approach to evaluate strategies.

Closing product and material loops is beneficial and contributes to sustainable development when it decreases both resource use and unwanted emissions relative to primary and linear production, and less effort is needed to collect and process used goods. Similarly, strategies that provide more net benefit in terms of resources are preferable. The results pertain to products of varying complexity, including electric and electronic components, textiles and advanced materials, and simple one-material reusable packaging. Conclusions for product and process development and further circular economy focus areas are highlighted. The results confirm a need to focus on retaining value and on avoiding negative value in the form of unwanted substances/components.

Further empirical studies are recommended to validate the results across more manufacturing companies with different variables relating to, for example, company size, industry sectors, product categories, and material types. Future research can also study, in detail, efforts required and their connections to other criteria; SMEs usually have fewer resources to evaluate technical feasibility and legal aspects and to create networks, thus requiring more effort. In addition, means to balance efforts to retain value with limiting unwanted content in products require continued empirical research. Furthermore, with increased social sustainability awareness, more standards, regulations and legislation will be introduced and adopted, which will require regular updates by companies to retrieve their products for value recovery.

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